Continuous and Periodic Sorption Cryocoolers for 10 K and Below

Lawrence A. Wade,[1] Alan R. Levy,[2] and Steve Bard[1]

[1]Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA 91109

[2]University of California at Santa Barbara
Department of Physics
Santa Barbara, CA 93106

ABSTRACT

This paper presents the current status of both continuous and periodic operation sorption cryocooler development for astrophysics missions requiring cooling to 10 K and below. These coolers are uniquely suited for cooling detectors in planned astrophysics missions such as the Exploration of Neighboring Planetary Systems, the Next Generation Space Telescope, and Darwin. The cooler requirements imposed by these missions include ten year life and the ability to scale designs to provide only a few milliwatts of refrigeration while consuming only a few watts of input power. In addition, the ExNPS and Darwin missions add stringent requirements for zero-vibration and zero EMI/EMC operation.

Spaceflight test results are summarized for the Brilliant Eyes Ten-Kelvin Sorption Cryocooler Experiment. This periodic operation sorption cooler is ideal for applications that require only intermittent operation at 10 K with quick cooldown capability (under 2 minutes). The experiment successfully provided flight characterization of all sorption cooler design parameters which might have shown sensitivity to microgravity effects. Full ground test performance was achieved with no indications of microgravity induced changes.

Ground test results from a continuous 25 K cooler planned for use in a long duration airborne balloon experiment are also presented. This 25 K cooler, which is in final integration and test, can be used as an upper stage for a continuous 10 K sorption cooler. Similarly, the potential benefits of using a 10 K sorption cooler as an upper stage for a 4 K cooler are also described. Finally, a NASA program to develop 30 K, 10 K and 4 K vibration-free coolers for astrophysics missions is outlined, which is planned to start in FY 1997.

INTRODUCTION

The heritage provided by the many successful dewar cooled missions (e.g. ISO, IRAS, COBE, and the now underway WIRE and SIRTF) has enabled the serious consideration and development of a new generation of actively cooled space instrument design concepts. The interest in cryocoolers being shown by the designers of these missions is a result of the substantial 'maculation of cryocooling technologies, which has occurred over t he past t en years, and of an increasing awareness within the scientific community of the potential benefits offered by these technologies. The utilization of long life cryocoolers allows mission designers to cool large format detector arrays during ten year missions. The volume and mass saved though the use of active coolers in combination with passive radiators enable mission designers to pack much larger telescope apertures into a given launch vehicle than would be possible in a dcwar cooled mission. '['INs, many of the missions that launch after 2005 will incorporate cryocoolers.

Astrophysics missions, now in the early design phase of development, which incorporate long-life, vibration-free cryocoolers include the Exploration of Neighboring Planetary Systems (ExNPS), the Next Generation Space Telescope (NGST) and Darwin. In addition to these precision pointing missions, moderate resolution missions such as FIRST and COBRAS/SAMBA arc incorporating low-vibration cryocoolers. This paper gives a discussion) of the state-of-the-art in sorption cooler technology and how recent work in the field is being directed toward the goal of producing sorption coolers for future spat.c based astrophysics missions.

FUTURE MISSION CRYOCOOLER REQUIREMENTS

Most of the mission concepts now under development will, for scientific, and engineering reasons first pointed out by the EDISON team,[1] operate in thermally advantageous orbits. Observing strategies and telescope/spacecraft configurations arc being developed to fully exploit these orbits, which place all of the ~300 K devices and structure together on a warm spacecraft bus oriented towards the sun and earth. The cold telescope and science instruments are remotely located from the warm spacecraft bus and thermally isolated by several radiative surfaces. This enables optical structures to be radiatively cooled as low as 20 K without the use of coolers or dewars.[2]

While passive radiative cooling is very effective when providing environmental shielding of extended structures and optics, it is often not very effective for absorbing actively generated loads (e.g. electronics, high bandwidth actuators, and detectors) at temperatures below 50 K, Typical requirements for astronomical telescope applications which require active refrigeration include cooling at one or more of the following temperatures: approximately 25 K for high bandwidth actuators, InSb, and QWIP detectors; between 4 and 8 K for Si:As BIB arrays; at 4 K for Si:Sb BIB arrays, SIS heterodyne receivers and for thermal sinking of magnetic, dilution and Helium-3 coolers used to cool bolometers to 0,1 K.

Several of the more challenging requirements for active coolers are well illustrated by the ExNPS mission. The ExNPS program is tasked to detect, image, and characterize planets around other solar systems, The ExNPS Planet Finder Array (PFA) consists of four 1,5 m telescopes on a 75 m baseline, passively cooled to 30 K, which arc operated as a nulling interferometer, a beam combiner that is also cooled to 30 K, and a detector that is cooled to 4 K. The PFA, along with its spacecraft bus and connecting structure, will be launched out to 5 AU using a Venus-Earth-Earth gravity assist trajectory on its nine year mission. The PFA must fit within an Atlas IIAS shroud (3.65 'm diameter by 9.4 m long with 5.3 m of the length tapering to a 0.81 m diameter tip) and within a lift capability of only 1824 kg. Due to the long duration of this mission, initially unfavorable thermal environment (especially during Venus flyby), and limited launch vehicle shroud volume and lift capability, it is not feasible to use a dcwar to support this mission.

The ExNPS PFA is designed to operate at 10 microns with a 20% bandwidth); using destructive interference to 'remove' the light from the central star, which is 1 ,000,()()0 times brighter than an cal-th-like planet would be. Combining the high resolution of this array and the need to null the target solar system central star leads to a pointing requirement of approximately $1\,()^{-6}$ arcseconds. Stirling and Pulse Tube coolers, or coolers using similar compressors, can not be used to actively cool the ExNPS PFA focal plane as the residual vibration perpendicular to the compressor axis is typically 0.25 N despite 9^{th} harmonic vibration nulling electronics.[3] To do better than this, three axis stabilization actuators would have to be incorporated into the compressor and expander, along with redundant actuators. Due to the high dimensional stability requirements (~ 10^{-10} m), stringent pointing requirements, and the difficulty of integrating this assembly into the beam combiner, use of these coolers is not deemed feasible

The solar array for this mission must be sized to enable observations at 5 AU when power is 25 times tougher to come by than at 1 AU. Therefore any cooler incorporated into the ExNPS design must have very low power requirements. To achieve this requirement, the cooler must be capable of taking full advantage of the favorable thermal environment enjoyed during observations anti to scale down to a size commensurate with the ExNPS PFA mission detector cooling requirement of approximately 5 mW at 4 K. An additional stringent requirement is imposed by the desire to do spectroscopy on the detected neighboring planetary systems. in this operational mode, the final signal is measured in electrons per hour. As a result, essentially no cooler induced EMI/EMC is acceptable.

Only sorption coolers can meet the stringent combination of life, vibration, mass, volume power, and EMI/EMC requirements posed by missions such as the ExNPS PFA.

STATUS OF SORPTION CRYOCOOLING TECHNOLOGY

Sorption Technology Summary

Sever-al review papers have been published which describe the history and basic concepts behind the various kinds of sorption coolers.[4,5] only a brief summary wiii be provided in this paper,

Sorption coolers are comprised of a sorption compressor, containing a sot-bent material, and a Joule-Thomson (J-T) expander, The refrigerant is selected to correspond with the required cooling temperature and the sorbent material is selected based on the choice of refrigerant and the available thermal environment. Cooling between 30 K and 8 K is achieved by use of metal hydrides as the sorbent material and hydrogen as the refrigerant. Cooling at **4** K and below is achieved using activated charcoal as the sorbent and helium as the refrigerant.

During operation of the cooler, compressed refrigerant, desorbed by a heated sorption bed, is expanded through a J-T orifice to create a gas/liquid refrigerant mixture. The liquid evaporates as it absorbs heat from the detectors and is then absorbed and repressurized in a cool bed, thus creating a fully reversible closed-cycle system. Due to the physics of the sorbent materials, the compressors work most efficiently when operated over a large pressure ratio at low mass flow rates. The combination of a sorption compressor with a Joule-Thomson expander provides a cooler, which operates without cold moving parts and has a capacity that can be scaled linearly to below 1 mW. All of the sorption cryocooler designs being considered for future astrophysics missions utilize passive radiative cooling at between **50** and **65** K to precool the refrigerant gas,

Design characteristics of sorption coolers which are important to mission designers include:

1) The ability to locate all warm components directly on the preferred heat rejection surfaces to both minimize system mass, simplify the mechanical design, and to prevent thermal parasitic into the passively cooled regions of the telescope;
2) Minimized cryostat size to simplify integration into the complicated final beam combiner or focal plane assembly regions;
3) Dimensional stability of order the amplitude of lattice vibrations in a simple block of stainless steel at ambient temperature (i.e. no vibration imposed beyond that normal to a passive piece of stainless);
4) Zero EMI/EMC effects on the science instruments;
5) Extremely low power usage. This can be achieved through taking full advantage of the thermal environment to minimize environmental loads, intercept parasitics, and to precool the refrigerant. Combining the aggressive use of the thermal environment with the ability to linearly scale the size and thereby the input power to the cooler results in extremely small

system power requirements. Predicted rule-of-thun~b performance ranges for coolers providing less than 100 mW of cooling and designed for flight are:[a]

a) 300-400 W/W at 20 K
b) 700-900 W/W at 9 K
c) 3000-5,000 W/W at 4K

Recent advances have substantially improved the flight readiness level of sorption technology. A cooler developed for periodic operation was flown in space in May, 1996 on the space shuttle Endeavour as part of the S'1'S-77 mission. This Brilliant Eyes '1'cn-Kelvin Sorption Cooler Experiment (BETSCE)[6,7] examined ail of the design characteristics which could be affected by the microgravity environment. The resulting flight dataset provides flight validation for the design of future periodic and continuous sorption coolers,

A continuous operation 25 K cooler is being developed for the l-University of California at Santa Barbara (UCSB) Long Duration Balloon (1 .DB) experiment[8]. The 25 K LDB cooler is the first hydride sorption cooler 10 help 'do' science instead of 'being' the science. This single-stage cooler was designed to robustly achieve stable performance while dramatically improving contamination tolerance.

Summary of BETSCE Flight Results and Accomplishments

BETSCE,[3,4] shown in Figure 1, is a periodic operation cooler developed to achieve a cold end temperature of less than 11 K in under 2 minutes from a starting temperature of 65 K. This experiment was flown on the space shuttle Endeavour during the S"1'S-77 mission which occurred in May, 1996. As the first hydride sorption cooler flight experiment, it offered a unique opportunity to measure microgravity effects on a wide variety of performance characteristics.

The in-flight performance of BETSCE has completely validated the usc of hydride sorption coolers in space as no on-orbit degradation was found. As shown in Figure 2, the cooler successfully achieved a cold tip temperature of 10.3 K in less than two minutes from an initial temperature of 70 K, The cooler provided 100 mW of cooling for 10 minutes. This exceeded the BETSCE performance goals. In addition, a total of 8 quick cooldown cycles to liquid hydrogen temperatures were accomplished, achieving a minimum temperature of 18.4 K. A total of 18 compressor cycles were completed and the ability to repeatably achieve the 10, 1MPa high pressures achieved in ground testing was successfully demonstrated.

The measured microgravity effects on characteristics of interest to all sorption cooler designers were:

1) $LaNi_{4.8}Sn_{0.2}$ and ZrNi hydride powder thermal conductivities were perhaps the most important properties to characterize well. The in-flight conductivities were determined, from the rate of absorption and the absorption pressure, to have been identical to those measured in a one-g environment.
2) Supercooling of the n-hexadecane phase change material in the Fast Absorber Sorbent Bed is important to most periodic operation cook designs and to some continuous cooler designs. No change in its expected 291 K melting temperature was observed,
3) The ability of the cryostat liquid reservoir to separate and retain both liquid and solid hydrogen substantiality affects cooler capacity anti temperature stability. Again, no adverse microgravity effects were observed in the cryostat cold head.

1 n summary, the BETSCE flight data shows that no additional design margin is required to design a hydride sorption cooler for space missions in addition, BETSCE clearly demonstrated the feasibility of successfully developing and flying a sorption cryocooler in space.

[a] The estimates are based on a 60 K precooling temperature and designs incorporating full flight and ground test safety margins. Therefore, a 5 mW, 4 K cooler can be built for flight which requires less than 25 W of input power. Similarly, a 20 mW, 9 K requirement can be met with less than 18 W of input power

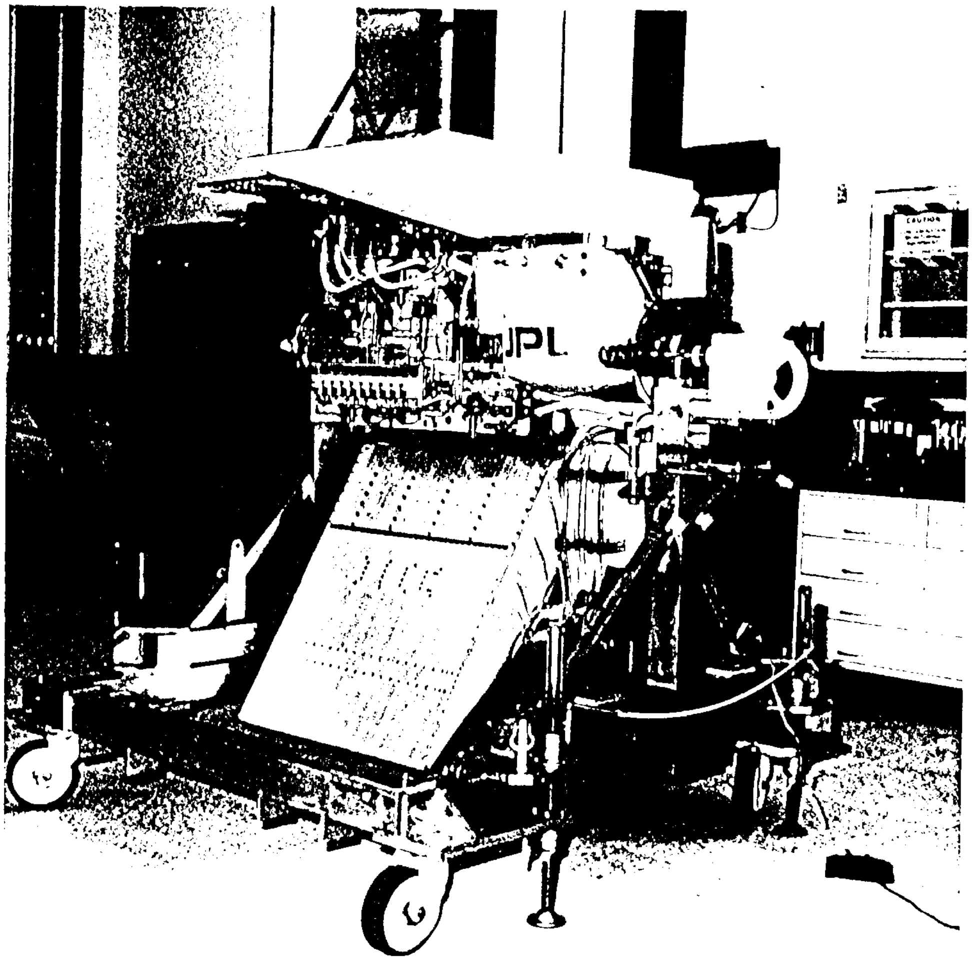

Figure 1. BETSCE mounted on ground support equipment cart at the Kennedy Space Flight Center just prior to integration with the space shuttle Endeavour.

DATA AVAILABLE UPON BMDO APPROVAL

Figure 2. BETSCE IOK flight cooldown data.

Status of 25 K UCSB Long Duration Balloon Cooler

A continuous operation **25** K single-stage cryocooler, shown in Figure 3, is currently in final integration and test at JPL in support of the first long-duration balloon experiment to measure anisotropy in the Cosmic Microwave Background radiation (CMB). The 25 K LDB cooler is designed to provide **480** mW of refrigeration using a measured 220 W of input power. Precooling of the hydrogen and thermal shielding of the focal plane is provided by two Sunpower Stirling cryocoolers. The final integration and performance testing of this cooler will be completed in fall 1996. Delivery and integration of this cooler into the UCSB dewar package will occur late in 1996. This UCSB LDB experiment is scheduled to fly over Antarctica for two weeks in December, 1997,

Since this cooler is the first hydride sorption cooler to be used to help gather science data, other than on the performance of the hydride cooler itself, it is also the first to be designed to support science instrument requirements. The use of this cooler in the LDB expel-imcnt has enabled the team at UCSB to realize substantial mission benefits by replacing their baselined 500 liter helium dewar. Future planned one to three month long flights would be impossible without active cooling,

For a balloon flight experiment such as LDB, the primary requirement is to achieve reliable and safe operation. This has to be achieved in tests conducted in a open lab environment by people familiar with only the basics of cooler operation, after transportation and test flights in New Mexico or Texas, and later transport to, and flight in, Antarctica, At the conclusion of the test flights, the balloon is separated from the payload and the science instrument parachutes to the earth from an altitude of approximately 40 km. The landing is not always smooth and substantial repairs are often required after these flights. In recognition of the rigors this cooler will be subjected to, its design permits all of the major components to be isolated by hand valves; thereby permitting removal and repair as required. Additionally, all refrigerant sealing joints are welded to

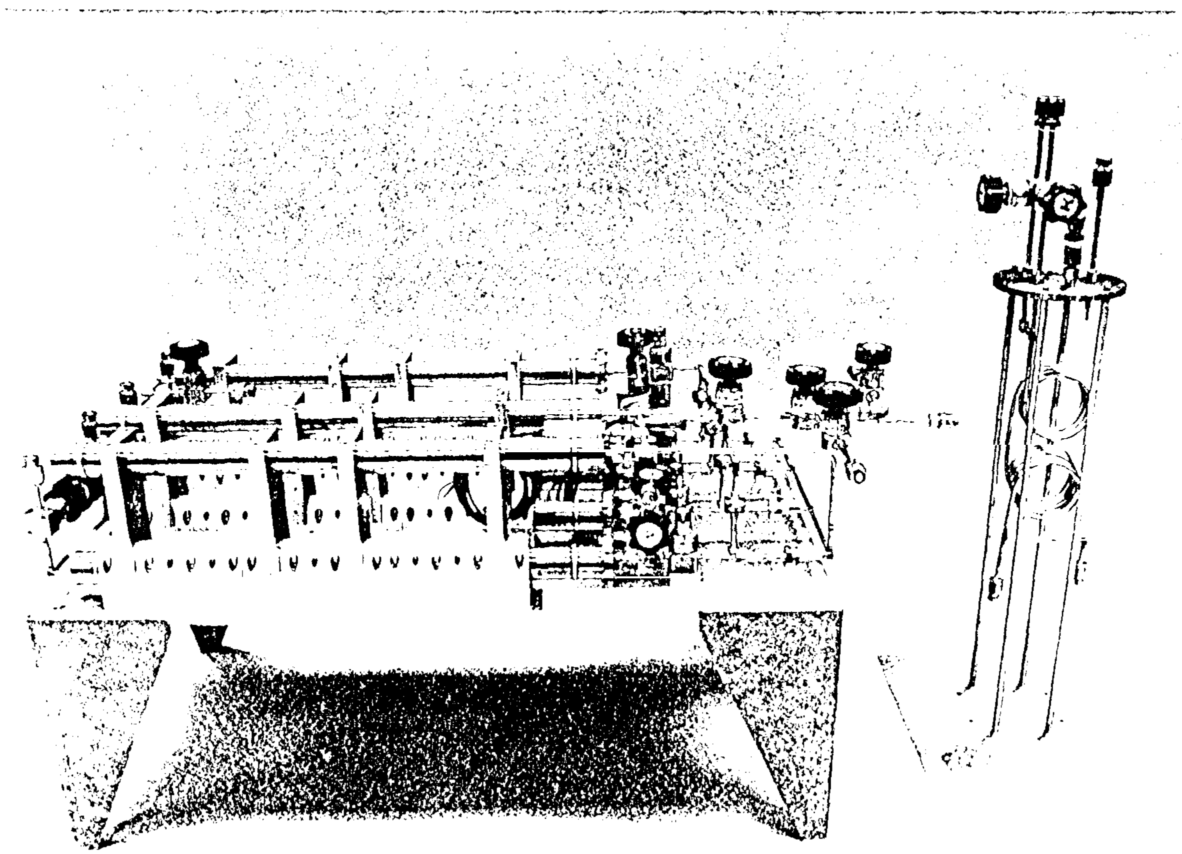

Figure 3. The 25 K UCSB Long Duration Balloon Cooler is shown when assembly was nearly complete The cryostat is to the right and is shown without the flight liquid reservoir and J-T attached.

support the high vibration levels and abusive handling expected during transportation and test 'flights. Because of the overriding concern to make the UCSB LDB cooler safe and rugged, it has been built at a level equivalent to flight engineering model hardware. Hence, all of' the materials selected, fabrication and assembly techniques and design and safety margins arc consistent with flight hardware requirements.

The most significant innovations in this effort, when compared to previous sorption coolers, are in the materials selection and fabrication processes used to minimize contamination levels. The primary reliability concern for any J-T cooler is contamination. To achieve high reliability and to provide a better foundation for future flight missions, the cooler structure was entirely made of 316L VI M/VAR stainless steel. The Department of Energy's Ames Laboratory at lows State University provided the $LaNi_{4.8}Sn_{0.2}$ hydride sorbent with a purity level over 10,000 times better than that used for fabrication of any sorption cooler before this. Assembly of the cooler was conducted entirely in a purified and monitored Argon glovebox. Vacuum p ump out ports were provided to each volume within the refrigerator.

The cooler has several features incorporated, which should enormously increase its tolerance to contamination. A 0.01 micron filter is placed at the inlet of the J-T expansion element. The temperature of the refrigerant at this point wiii bc approximately 35 K. At 35 K even i ppm of air constituents, such as oxygen and nitrogen, arc frozen and can be filtered out of the refrigerant stream. Porous plugs with a diameter of approximately 0.2 cm are used for the actual expansion rather than the <0.002 cm diameter orifices more commonly chosen.

To reduce the cooler mass and power, novel, miniature ZrNi hydride sorbent beds (O. 6 cm diameter by 2.5 cm long) arc used to activate the compressor element gas gap thermal switches. The other novel features arc the inclusion a high pressure refrigerant reservoir and a low pressure sorbent bed to ensure the 1 mK/s stability of the cold temperature required by the UCSB radiometer.

This demonstration that a hydride sorption technology can be fabricated in a lightweight, integratable package, and operate reliably despite a challenging environment wiii substantially advance the state-of-the art, The proof of detector compatibility, as demonstrated hy the quality of' the science data gathered, and verification of cooler reliability and ruggedness will substantially advance the heritage of sorption cooler developed for future astrophysics missions.

Cooling to Ten Kelvin and Below

(continuous operation expanders for use below 10 K with hydrogen, originally proposed by Jones,[9] are currently under active development. As hydrogen is a solid at this temperature with a vapor pressure of oniy 1,9 torr, a novel expander is used. Longsworth and Khatri[10,11] recently described a successful laboratory test of such a device, Operation of this expander is initiated by using a standard J--l' expansion technique to collect a small amount of liquid hydrogen in a reservoir. If a pump (or sorbent bed) is then used to evacuate the liquid reservoir which has a porous filter at its exit, a solid is formed. Stable continuous operation is then achieved: resulting in a liquid reservoir with a temperature gradient which turns into a solid. As the solid sublimates tile heat of fusion conducts back to the liquid reservoir to freeze replacement refrigerant and the heat of vaporization serves to provide useful refrigeration. Tests demonstrated that this 'glacier cooler' operated in a stable and repeatable manner at 9.7 K,

A minor variation of this device has been proposed by L. A, Wade, which permits two-stage operation of this cooler. This can be achieved through either of the following two methods. The conceptually simpler of these uses a common high pressure gas supply which is manifolded into two J-T expanders. One of these expands to a standard two-phase gas/liquid hydrogen mixture. The liquid hydrogen is separated and retained in a wick to provide thermal shielding for the cold stage and perhaps to provide active cooling for devices as needed. The vaporized hydrogen from this reservoir is returned to a compressor containing a medium pressure hydride sorbent, such as

$LaNi_{4.8}Sn_{0.2}$, at a nominal 0.1 MPa. The second J-T expander is identical to the Longsworth and Khatri design. This reservoir vents into a low pressure hydride sorbent such as ZrNi.

An alternate configuration would combine these two devices by using a single J-T to form a single, and therefore common, liquid reservoir. Two vents are provided: one to the medium pressure sorbent bed and the other to the low pressure bed. A heat exchanger at the medium pressure vent location is used to connect to a thermal shield about the low temperature part of the cryostat.

4 K sorption coolers have been proposed for many years.[12] in the past however the cooling requirements envisioned were usually between 0.1 and 1 W. The resulting power requirement quickly stopped the further development efforts. Reduced cooling requirements, coupled with the recent availability of hydride sorption coolers have made use of these helium/charcoal coolers possible.

A typical three-stage cooler concept is to use an activated charcoal, such as Saran carbon, cooled to 16 K by the first hydride stage as the sorbent material. The high pressure helium refrigerant is then precooled to 9 K using the second hydride stage of the cooler, To further improve efficiency during desorption, the charcoal compressors are heated by the high pressure hydrogen refrigerant to approximately 40 K. This improves the overall cooler efficiency by precooling the hydrogen refrigerant from the nominal 60 K to 40 K thereby increasing the amount of refrigeration per unit massflow in the first two cooling stages. The hydrogen gas manifolding for accomplishing this can be done either by separately plumbed lines which directly connect the appropriate compressors or through use of valves,

FUTURE SORPTION COOLER DEVELOPMENT PLANS

The primary thrust for the continued development of sorption cryocooler technology will be provided by a NASA Code X research and development funded program planned to start in FY 1997. This effort will be focused on developing a series of vibration-free cryocoolers at 30 K, 6 to 10 K and 4 K in support of precision pointing NASA astrophysics missions such as I:xNPS and NGST. These coolers will be developed at an engineering model level and integrated into a series of challenging science experiments in a manner similar to that followed in the 25 K LDB cooler effort.

The quality of the science data derived from these experiments will prove the most stringent characterization of the ability of these coolers to compatibly integrate with the science instruments. Following this path is considerably more useful and cost effective than developing sepal-atc]y the laboratory facilities required. As an example, integrating such a cooler with an ground based in frared interferometer provides far more useful information as compared with developing a 30 picometer cryogenic metrology station for dimensional stability testing in the laboratory,

The planned FY'97 effort will start with component development to determine the two major open issues remaining in sorption cooler- development:

1) Can a sorption compressor operate with stable performance for ten years of continuous operation?
2) Can the continuous operation, sub- 10 K, hydrogen sublimation cryostat developed by Longsworth and Khatri provide stable long term cooling? And if so, at what minimum temperature?

It appears that the last remaining challenge to operating a hydride sorption compressor for ten years is caused by the slow disproportionation of La from $LaNi_{4.8}Sn_{0.2}$ into LaH_2 and similarly of Zr from ZrNi into $ZrH_{1.5\ to\ 2}$. Measuring the heat of reaction of these processes will permit a maximum temperature to be selected at which the disproportionation reaction will be too slow to significantly affect compressor performance over a ten year period. Calculations by Wade indicate that this is so for $LaNi_{4.8}Sn_{0.2}$ when operating at a maximum temperature of 480 K. This lowered maximum operating temperature reduces the maximum operating pressure to 8 MPa from the typically baselined 10 Ml'a, Once an accurate measurement of' these heats of'reaction with flight grade hydrides has been made, compressors will then undergo life testing to verify the stability predictions.

The second major issue, cryostat minimum temperature and temperature 'stability, will be addressed though development and testing of a series of two-stage cryostats at 10 K and below. in ground tests, the BETSCE cooler and the Proof of Principle cooler[13] both demonstrated operation to 9 K. Neither of these cooler designs were optimized for operation below the 1.9 torr vapor pressure of 10 K hydrogen. The 0.0018 torr, 290 K equilibrium pressure of the ZrNi sorbent used in these coolers is 70 times lower than the O. 129 torr vapor pressure of normal hydrogen at 8.11 K. It is therefore not unreasonable to think that operation to below 8 K is possible for a hydrogen sorption cooler at low refrigeration load.

The results of these efforts will then be fed into the development of a continuous sub-1O K cooler which is planned to start in FY 1998. This effort in turn will support the future development of's continuous operation 4 K cooler.

SUMMARY

Most of the sorption cryocooler development being actively pursued is focused on coolers which provide continuous cooling at temperatures below 30 K and at loads of well under 0.1W. The successful flight of the BETSCE cooler has clearly demonstrated the suitability of sorption technology for spaceflight applications. The transition of these coolers from a development level primarily concerned with technology demonstration to one primarily concerned with supporting aggressive science missions has been initiated with the development of the 25 K LDB cooler.

It seems reasonable that with the planned development efforts, sorption coolers will reach maturation and, in doing so, enable several of the most ambitious and exciting scientific missions yet conceived.

REFERENCES

[1] Thronson, Jr., 11, A., et al, "*EDISON: The Next Generation Infrared Space Observatory,*" *Space Science Reviews*, Kluwer Academic Publishers (1 992), vol 61, pp 145-169.

[2] Wade, L. A., Kadogawa, H., Lilienthal, G. W, Terebey, S., Rourke, K., Harwarden, T., "Mid-InfraRed Optimized Resolution Spacecraft (MIR ORS)," To be published in the SPIE proceedings of the Space Telescopes and Instruments 11 meeting, in Denver, CO, August (1996).

[3] Smedley, G. 'P., Johnson, D. L., Ross Jr., R. G., *TRW IW-35 K PulseTube Cryocooler Performance Characterization*, JPL Internal Document 1)-1 3236, Jet Propulsion Laboratory, Pasadena, CA (1995), Fig 7.7.

[4] Wade, L. A., "Advances In Cryogenic Sorption Cooling, " *Recent Advances In Cryogenic Engineering-1993*, ed, 11>' J. 1). Kelley and J. Goodman, American Society of Mechanical Engineers, New York, NY. HTD-Vol. 267 (1 993),])]),57-63,

[5] Wade, L. A,, "An Overview of the Development of Sorption Refrigeration," *A dvances in Cryogenic Engineering*, Plenum I)rcss, NewYork(1991), vol. 37 , pp. 1095-1105,

[6] Bard, S,, et al. "10 K Sorption Cryocooler Flight Experiment (BETSCE)," *7/h International Cryocooler Conference Proceedings*, Phillips Laboratory, Kirtland Air Force Base, NM (1993), 1'1X1'--93- I 00 1, pp 1107-1119.

[7] Bard, S., et al. "Flight Demonstration of a 10 K Sorption Cryocooler," to be published in *Cryocoolers-9*, Plenum Press, New York (1 997).

[8] Wade, L. A., and Levy, A. R., "Preliminary Test Results For A 25 K Sorption Cryocooler Designed For The UCSB Long Duration Balloon Cosmic Microwave Background Radiation Experiment," to be published in *Cryocoolers-9*, Plenum Press, New York (1 996).

[9] Jones, J. A., "Hydride Absorption Refrigerator System for Ten Kelvin and Below," *Proceedings of the Third Cryocooler Conference*, NBS *special* Publication 698, NBS, Boulder, CO (1984).

[10] Longsworth, R. C. and Khatri, A.. "Continuous Flow Cryogen Sublimation Cooler," to be published in *Advances In Cryogenic Engineering*, Plenum Pros, New York (1996), vol. 41.
[11] Longsworth R. C. and Khatri, A. N., "Continuous Flow Cryogen Sublimation Cooler," *U.S. Patent 5,385,027*, Jan. 31, 1995.
[12] Hartwig, W, H., "Requirements for and Status of a 4.2 K Adsorption Refrigerator Using Zeolites," *Proceedings of the Conference on Refrigeration for Cryogenic Sensors and Electronic Systems*, Boulder Colorado, NBS SP 607 (1980),
[13] Wu, J. J., et al, "Experimental Demonstration of a 10 K Sorption Cryocooler Stage," *Advances in Cryogenic Engineering*, Plenum Press, New York (1991), vol. 39, pp. 1507-1514,

depending on the mission and instrument payload size. The Advanced Bus "AB600" structure has been selected for incorporation into the SSTI 'techsat'. Advanced Bus technology will also be used for the EoS common spacecraft bus, SMTS and the 12 proposed Odyssey personnel telecommunicat ions satellites. These spacecraft arc designed to survive planetary environments, including 100 krad total dose tolerance considered sufficient for the 5 year MIRORS mission.

The Ml RORS version of the AB600 spacecraft will be three-axis stabilized with pointing accuracy of 1 arcminute. The use of a tip-tilt mirror for fine image stabilization enables the spacecraft pointing requirements to be considerably relaxed, permitting inexpensive and light momentum wheels to be used for coarse pointing and slewing. Monopropellant hydrazine thrusters, located on the sun side of the solar shield, operate in a blowdown mode to provide the required Av for orbit maintenance and attitude control over the planned five year mission with less than 50 kg of propellant. Preliminary studies indicated that there is little likelihood of significant contamination buildup on the cryogenic surfaces duc to the shielding provided by the v-groove radiator, the open nature and large area of the cryogenic surfaces, and the relatively high vapor pressure of hydrazine propellant decomposition products.[9] If further study shows contamination to be a problem, alternative propulsion approaches can be used, such as nitrogen and helium cold gas propulsion.

The selected MIRORS spacecraft bus will satisfy requirements for launch in either a Titan 11 or Med-Lite launch vehicle fairing. A performance summary is provided in Table 1. Spacecraft power is provided by a low cost sun-oriented silicon array and a small battery (Ni Cd or NiH_2) for short duration eclipse periods and off sun-attitude operations. The solar array is sized for operation at the maximum off solar axis angle. An 8 Watt x-band transmitter will achieve the required 50 kbps telemetry rate with a 0.5 m spacecraft antenna and a 10 m ground station. Two S-band onmi antennas arc used to provide routine and contingency spacecraft control operations. A four Gb solid state recorder is base] ined. The on board computer is a radiation hard 1750 A processor.

1.7 Mission operations and data handling

Long life operation provides both difficulties and opportunities in the mission design. The challenge is to operate inexpensively enough that the full mission life can be affordable used for the gathering of science data.

Mass Summary (kg)	
Spacecraft Bus (including contingency)	215
Telescope/Radi ators	300
Propellant (delta v and attitude control)	50
Total	56S
Launch Vehicle (Med-Lite, lunar (flyby) transfer to L_2)	680
Margin	115
Power Summary (W)	
Spacecraft Bus (including contingency)	150
Payload	200
Total Spacecraft Power	350
Solar Array Output (Silicon, 4 m^2)	400
Margin	50
Performance Summary	
Payload Mass	300 kg
Payload Power	200 w
Attitude Control Pointing Accuracy, 3 sigma	60 arc scc
Attitude Control Jitter, arc scc, 3 sigma	0.1 arc scc
Downlink data rate	50 Kbps
Data Storage	4 Gb

Table 1. MIRORS System Summaries

The commands required to slew the instrument and for daily operation will be autonomously generated. Aggressive use of on-board processing using workstation class CPUS (e.g. the newly flight qualified RAD6000) will permit real time command generation for active pointing, slewing operations, absolute pointing knowledge generation, etc. The baselined TRW Advanced Bus spacecraft already incorporates a number of software features which greatly reduce the need for an engineering ground support team. A university class ground stat ion with a 10 m antenna is envisioned to further reduce expenses. WC estimate that 1o ssIcss compression of the largest expected dataset will permit transmission at 50 kbps in only 2 hours pcr day.

Uplinked transmission will bc minimized. The environmental stability provided by this orbit enables the normal housekeeping mission operat ions team to bc virtually eli minated wit h only software triggered engineering support required. A low level of support for navigation and data reception/command uplinks will be needed. Together with science team support, wc project that mission operations can be accomplished for under $2M pcr year over the 5 year projected mission lifetime. A higher level of support during the first year will bc required for orbit insertion, initial system calibration, and align ment.

1.8 MIRORS sensitivity compared with other infrared instruments

With existing infrared detectors MIRORS will bc background limited by zodiacal emission. Figure 4 shows the photon flux pcr square arcsecond versus wavelength for various backgrounds. The thermal background due to the optics of the telescope is modeled as a greybody (i.e. blackbody assuming 3 percent emissivity optics). The middle curves labeled 20, 30, and 40 K arc relevant for MI RORS. The curves labeled z_{ir} and z_{scat} arc the thermal and scattered light components of the solar

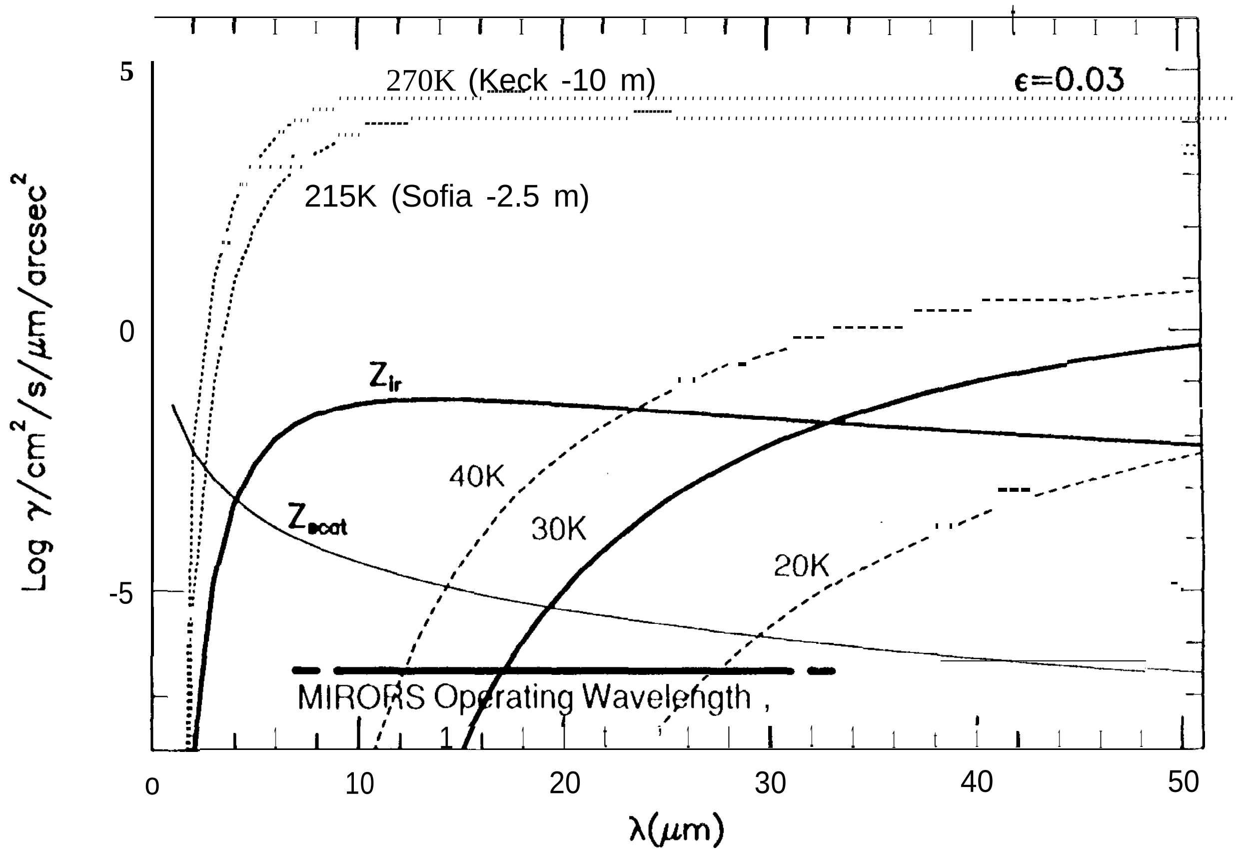

Figure 4. Photon flux per square arcsecond versus wavelength for several background types. The T = 270 K curve is only relevant for windows where the atmosphere is partially transparent (20, 10, and <5 microns).

system's zodiacal cloud. The intersection of z_{ir} with the T = 30 K curve shows that MIRORS is background limited by thermal zody below 30 microns.

The T = 270 K cum shows the thermal background for ground based telescopes. This is relevant for windows where the atmosphere is partially t ransparent (20, 10, and < 5 microns). The advantage of cold optics in space is immediately clear: the zodiacal background limit is four to five orders of magnitude smaller than emission from a "warm" ground based telescope.

Nonuniformity ics in existing array detectors limit performance to 1 % of background. New micro-scanning techniques developed for 1S0 improve performance to 0.1 % of background, This sets a limit to the sensitivity of 0,5 μJy/arcsec^2 at 10 microns (1 σ). These values change by less than a factor of 2 out to 30 microns. The corresponding integration time is 110 scc for the MIRORS 5.34 m^2 effective area and 20°/0 bandpass. At 10 microns, the instantaneous MIRORS beam is 0.5" x 0.5" = ().25 arcsec^2, which implies a point source sensitivity of 0.125 μJy. MI RORS's sensitivity is about a factor of 10^5 better than IRAS and a factor of 300 better than 1S0. It should be noted that flat fielding performance in some current optical and near infrared detectors approaches 10-5 of background If mid-infrared detectors can also be made to work at this level, Ml RORS's sensit ivity will improve by 2 orders-of-nlagnitudc for wavelengths shorter than 24 microns. At longer wavelengths, the sensitivity is limited by the 30 K optics.

Estimates of confusion from extragalactic point sources and structure in the galactic cirrus[10,11] arc uncertain at these low flux levels. Extrapolating Gautier's study[12] wc predict a confusion limit lcss than 1 μJy at wavelengths below 30 microns except where the galactic diffuse emission is brightest. Extrapolation of 1S0 predictions'[3] suggests that asteroid confusion affects MI RORS mar the ecliptic plane (± 10°) for integration times longer than 500 seconds (asteroids move). In summary, it appears that MIRORS may be confusion limited in regions of bright galactic cirrus *or* by asteroids when near the ecliptic plane, For ot hcr regions, Ml RORS will be pattern noise (flat field) limited. Results from near-tcrtn infrared missions like 1S0, and later SIRTF, will greatly help to quantify these limits. However, it is certain that MIRORS will have a big advantage over smaller precursor telescopes in its operating wavelength range: both because high spatial resolution beats down source confusion limits, and because of its larger collecting area.

2. SMALL MISSION W? RS1ONS OF MIRORS

Wc have also considered a 2 m aperture version of MI RORS, which would provide a near term technical feasibility demonstration for future JR telescopes such as the Next Generation Space Telescope (NGST), while still achieving superb science. As in the baselined Ml RORS mission, the telescope in this system would be pointed perpendicular to the spacecraft/sun line to enable full sky observations. The tcc shaped primary would be composed of two fixed segments, 2 m by 0.5 m and 1.5 m by 0.5 m arranged with the FPA in an off axis position located between the passive radiator and the aperture. The only element of the optical system needing deployment would then be the secondary. Similarly, no deployment of the solar shield and passive radiators would be required in this smaller MI RORS. This permits the shields to be inexpensively made out of sheet aluminum.

This small version of MIRORS would still incorporate passive cooling to <25 K with active cooling of the FPA below 8 K. The 2 m aperture has a collecting area of 1.75 m^2, nearly 5 times that of 1S0. Other important technical demonstrations achieved by this small version of MI RORS include active image stabilization and tracking, compatibility of a low cost commercial spacecraft bus with a precision pointed astrophysics mission, nearly autonomous operation at L_2, and optical alignment with cryogenic set-and-forget actuators.

The primary accomplishment of an early flight of a spacecraft like this would be the demonstration that high resolution astrophysics can be successfully accomplished within a severely cost constrained environment.

3, CONCLUSIONS

By nature, the partially filled aperture mirror represents a hybrid between normal filled aperture mirrors and interferometry. The MIRORS partially filled aperture concept attempts to use modest extensions of available technology in a novel way and [hereby offers a near term path to greatly increased spatial resolution. The ncw technologies incorporated into the MIRORS mission concept separate this cffort from previous studies such as the Largc Deployable Reflector (LDR). Provided continued tcchnical dcvelopmcnt, wc confidently model program costs for a 5 meter aperture mission in 2005 as being within thc $200M cap assumed for this study. The potential to develop an inexpensive large aperture telescope distinguishes MIRORS as a unique tool for the cxploration of space in the post-SIRTF timeframe,

The technical 'tricks' integrated into the MIRORS design could cnablc a tclcscopc, with an aperture thc size of the Hale Telescopc's, to bc flown in space in the reasonably near future at an affordable budget. It must be recognized that without continued technology dcvelopmcnt scvcral of the novel technologies outlined below will only be available as concept demonstrations (lab toys). It is assumed that significant rcsourccs will bc cxpcndcd which results in functional flight-grade hardwarc being made available to future flight missions. The innovations incorporated into the MIRORS concept which are likely to bccomc part of any post-SIRTF IR astrophysics mission include:

1. A tcc shaped partially filled array, combined with image reconstruction techniques, to enable high spatial resolution imaging at substantially rcduccd mass and volume.

2. The spacecraft configuration and thermal design innovations embodied in MIRORS rcprcscnt a substantial cost and mass savings over the designs traditionally used. Operating at L_2 enables a spacecraft design which places all of the warm elcments together, facing the sun and earth to allow continuous power and communications, while permitting easy thermal isolation of the cryogenic tclcscopc and elimination of the optical tube assembly. The spacecraft configuration proposed here, in combination with the choice of a Lissajous L_2 orbit rcprcscnts a near-optimum thermal solution. Combining this orbit selection with inflatable v-groove radiators and solar shield, and vibration-free sorption cryocoolcrs offers a wide range of thermal control opportunities to benefit other astrophysics missions.

3. Cryogenic actuators enable incxpcnsivc, low precision structurcs and supcrfinc active pointing. The usc of set-and-forget zero heat dissipation actuators for optical alignment, hugely simplifics the task of cooling the optical structure. Arguably, it is only with such an actuator that passively cooled PFA tclcscopcs are practical.

4. inflatable shields for blocking views of the earth/sun and also for staged cryogenic cooling substantially reducc systcm mass at the cost of additional settling time after slewing between targets. However, coupling inflatable shields with a long-life mission design more than makes up for the loss of observing time.

s, Combining a low cost commercial spacecraft bus with an active image stabilization and fine pointing device to enable incxpcnsivc, long-integration time imaging is perhaps the most successful of the proposed design techniques to reduce systcm mass and cost. In particular, the actuated Offner relay solution successfully achieves all of the performance rcquircmcnts for such a precision pointed imaging mission. In addition, the relay enables simple and effective stray-light control to be incxpcnsively implemented.

6. Large Focal Plane Arrays enable high resolution, while maintaining a large telescope field-of-view. The continued development of such arrays (QWIP's, Si:As BIB's and Si:Sb BIB's) is central to all future infrared astronomy. Combining the usc of these relatively high heat dissipation arrays with active coolers enables long-life, low mass missions.

7, Mission operations arc greatly simplified by the sclcctcd observing strategy, orbit selection and spacecraft configuration. The stability of the resulting design enables many of the tasks traditionally handled on the ground, such as thermal [rending, to bc done autonomously with built in fail-safes used to alert the engineering team should an anomaly occur. Similarly, thc observations arc done in such a constrained and predictable manner, that the detailed operating commands to point from target to target, image, and station keep can all be easily handled on-board, This kind of semi-autonomous operation, which corresponds to remote observation with ground based observatories, will certainly become the hallmark of spacecraft operations in the early part of the next century.

4. ACKNOWLEDGMENTS

The support for this study by Bill McLaughlin through JPL B&P funding is gratefully acknowledged, The authors also wish to thank Don Rapp (JPL), Ray Garcia (JPL), Martin Lo (JPL), Dennis Thompson (Kodak), Charles Lawrence (JPL), Doug

Packard (JPL), Don Moore (JPL), Jeff Umland (JPL), Tim Krabach (JPL), Mike Ressler (JPL), Simon Collins (JPL), and Dana Bachman (Franklin and Marshall College) for their substantial help and wisdom.

5. REFERENCES

[1] Hawarden, T. G., Cummings, R. O., Telesco, C. M., Thronson, Jr. H. A., "Optimised Radiative Cooling of Infrared Space Telescopes and Applications [o Possible Missions," Space Science Reviews, 61, 113-144, 1992.

[2] Wilson, T. and Genberg, V., "Enabling Advanced Mirror Blank Design Through Modern Optical Fabrication Technology," Advanced Optical Manufacturing and Testing IV, V. Doherty, ed. Proceedings of the SPIE, 1994.

[3] H. Kadogawa, and L. Wade, "Scanning Offner Relay for Simplified Telescope Fine Pointing for Image Stabilization," NASA New Technology Report NPO-19567, NASA Tech Briefs, 60, June 1996.

[4] Aumann, H. }1., Fowler, J. W., and Melnyk, M., "A Maximum Correlation Method for Image Construction of IRAS Survey Data," Astronomical Journal, 99, 1674, 1990.

[5] Cao, Y. Prince, T.A., Tercbey, S., and Beichman, C. A., Publ. Astron. Sot. Pac., 108, 535, 1996.

[6] Wade, L. A., Levy, A. R., and Bard, S. "Continuous and Periodic Sorption Cryocoolers for 10 K and Below," to be published in Cryocoolers-9, ed. by Ross, R, G., Plenum Press, New York, 1996.

[7] Bard, S , Wu, J., Karlmann, P., Mirate, C. and Wade, L., "Component Reliability Testing of Long-Life Sorption Cryocoolers," Cryocoolers-8, ed. by Ross, R.G., Plenum Press, 1995.

[8] Wade, L. A., and Levy, A. R,, "Preliminary Test Results For A 25 K Sorption Cryocooler Designed For The UCSB Long Duration Balloon Cosmic Microwave Background Radiation Experiment," to be published in Cryocoolers-9, Plenum Press, New York 1996.

[9] Honig, R. E., and Hook, H. O., RCA Review 21, 360, 1960.

[10] Helou, G., and Beichman, C. A. 1990, Proc. 29th Liege International Astrophysical Colloquium: From Ground-Based to Space-Borne Sub-mm Astronomy, Liege, Belgium 3-5 July 1990, ESA SP-3 14, 117.

[11] Gautier, T. N., Boulanger, F., Perault, M., and Puget, J. L., AJ, 103, 1313, 1992.

[12] Gautier, T. N., The First Symposium on the Infrared Cirrus and Diffuse Interstellar Clouds, pASP vol 58, ed. R. M. Cutri and W. B. Latter, p 115, 1994.

[13] Helou, G. 1994, IPAC Memo 94-1 S0-01